QUALITY AND CONTROL

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MORPHOLOGICAL APPROACH TO TAKING CORRECTIVE ACTIONS IN QUALITY CONTROL SYSTEMS FOR LAMINATED GLASS PRODUCTION

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A morphological approach to supporting decisions made to adjust the operating regime of process equipment on the basis of an analysis of statistical data is described. The method is considered as an example for adjusting the mollification temperature in laminated glass production.

Controlling processes on the basis of operative factors is fundamental and in most cases requires statistical thinking and application of statistical methods. This refers to all processes, including technological. A technological process must ensure that the product meets all requirements, i.e., quality indicators whose value falls within the tolerances for them. The process must give only a small variance of the quality indicators and it must be stable (the average value and standard deviation must be constant). If the technological process deviates from the center of the tolerance field, the total level of the discrepancies increases. As variability increases (standard deviation increases), the level of the discrepancies on both sides of the tolerance also increases [1].

Shewhart control charts are widely used to analyze technological processes. They are used as a diagnostics tool to determine the statistical controllability of a process, i.e., the presence or absence of special reasons for variability. The interpretation of the control charts can lead to one of two assertions: the process is statistically controllable or the process is statistically uncontrollable [2].

The question of choosing corrective actions has not been adequately formalized. The seven quality-control tools and seven planning and control tools proposed in 1979 by the Japanese Union of Scientists and Engineers are not a worthwhile solution. On the one hand, they are oriented toward solving problems which arise at the design stage, and on the other hand the suggestion is made that verbal assertions made by experts and highly qualified specialists be used instead of the correct numerical data.

The present article examines a method for making adjustments on the basis of a formalized analysis of the statistical data collected in the course of the technological process for the example of the production of laminated glass for the automobile industry. Mollification is a "critical" process which determines the geometry and parameters of the finished glass [3]. The mollification regime is monitored with 150 thermocouples placed in the crown and bottom of the furnace along the width and length of the chambers. The dimension of the system describing the temperature regime for the mollification of glass was substantially decreased by methods of cluster and multiple correlation analysis [4]. Thirty eight representative pulses, sufficient for monitoring the mollification temperature regime, were separated by analyzing the experimental data.

Statistical data on the temperature regime of the operation of the mollification furnace according to indications of the sensors singled out were used to assess the quality of the adjustment of the process. The temperature regime in the chambers of the mollification furnace is characterized by stationarity and high accuracy. The coefficient of temperature variation with respect to the average level does not exceed 2.9% in the preheating chamber and 3.1% in the main chamber, and it reaches 10.6% in the annealing chamber. The probability density distribution for the temperature at the points monitored differs from the normal distribution. This is indicated by the computed values of the coefficients of asymmetry and excess of the histograms.

The stability and accuracy of the temperature regime of mollification are important indicators of the execution of the technological process for producing triplex, but they do not completely determine the quality of the product, since other factors can also affect the quality. Consequently, it is important to determine how well the technological process is debugged and adjusted on the basis of quality indicators for the product and the level of defectiveness [5]. The quality of the glass can be assessed according to the probability density

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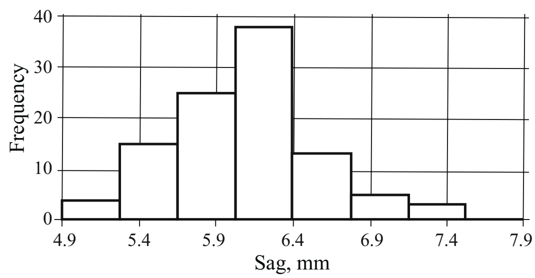

Fig. 1. Distribution of the sag of laminated glass.

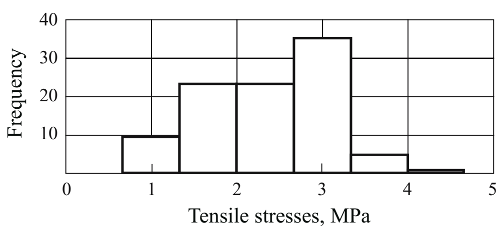

Fig. 2. Tensile stress distribution at the control point CP5.

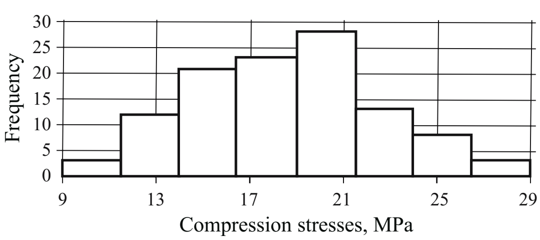

Fig. 3. Compression stress distribution at the control point CP7.

distribution of deviations of the glass surface from a reference surface of a control template (sag) and the distribution of the tensile and compression stresses along the border of the glass. One method for estimating the distribution density is to construct a histogram [6]. As an example, Figs. 1 – 3 present example histograms of the distribution of the quality indicators at certain control points (CP) constructed on the basis of 103 changeable data points.

According to the histograms (see Fig. 1) and the statistical data, the sag varies from 5.1 to 7.5 mm, and it falls within the admissible range of variation (4 – 8 mm). The arithmetic-mean value of the sag is 6.1 mm and is essentially identical to the center of the tolerance. The standard deviation of the sag is 0.49 mm. In time, in the course of production, the standard deviation of the sag can increase, which can result in a process which is neither reproducible nor controllable. Consequently, it is important to take measures beforehand to decrease the standard deviation of the sag of the glass in the course of glass production, i.e., produce a reserve of stability, as is conventionally done in automatic control systems. Taking the stability reserve to be a factor of two, we determined the admissible standard deviation of the sag in the technological process of fabricating glass, which should be 0.25 mm.

TABLE 1.

Control point	Tensile stress, MPa		
	average	minimum	maximum
CP1	2.24	1.04	4.69
CP5	2.21	1.04	4.17
CP8	3.35	0.52	5.21
CP10	2.52	0.52	4.69

TABLE 2.

Corrective action	Control point			
	CP1	CP5	CP8	CP10
Displacement of the average tensile stress, MPa	– 0.87	– 0.61	– 0.87	– 0.61
Decrease of variations	–	–	By a factor of 1.5	By a factor of 1.3

The histogram of the distribution of the tensile stresses at the control points differs from the normal distribution (see Fig. 2). Statistical estimates of the distribution of the tensile stresses in the production glass are presented in Table 1.

The magnitude of the adjustments to the tensile stresses was determined taking account of the tolerance field of tensile stresses along the border of the glass 0 – 4 MPa (Table 2). At all control points, the center of the tensile stress distribution must be displaced in the direction of lower values, and the variability of the stresses at the points CP8 and CP10 must be additionally decreased by a factor of 1.5 and 1.3, respectively.

The distribution of the compression stresses at the control points along the border of the glass differs from a normal distribution. As an example, Fig. 3 displays a histogram of the distribution of compression stresses at the control point CP7. The minimum value of the stresses is close to the bottom admissible limit 10 MPa. Negligible stress fluctuations can result in violation of the technical requirements imposed on an article. The statistical data from measurements of the surface compression stresses in the laminated glass produced are presented in Table 3.

The centers of the compression stress distribution at the points CP1 and CP7 must be shifted in the direction of increasing values by approximately 2.4 MPa to ensure a stress reserve similar to that at the control points CP5 and CP11.

Mathematical models describing the dependence of the quality indicators on the temperature regime for mollification were developed to generate corrective actions to improve the quality of laminated glass. Linear regression equations were chosen to describe the quality indicators of the glass taking account of the stability and accuracy of the execution of the technological process. The least-squares method was used to estimate the parameters in the regression model.

TABLE 3.

Control point	Compression stress, MPa		
	average	standard deviation	minimum
CP1	14.7	1.9	10.4
CP5	20.0	3.5	12.8
CP7	18.5	3.9	9.9
CP11	19.6	3.6	12.0

The sag of the glass is adequately described by the following equation:

$$y = 2.2 - 0.008T_{15} - 0.005T_{16} + 0.056T_{17} - 0.11T_{19} + 0.027T_{22} + 0.005T_{23} - 0.131T_{26} + 0.021T_{27} - 0.045T_{28} + 0.008T_{32} + 0.021T_{33} + 0.185T_{37} + 0.001T_{38} - 0.013T_{45} - 0.026T_{48} + 0.04T_{49},$$

where y is the magnitude of the sag, mm, and T_i is the temperature in the mollification furnace chambers, °C (i indicates the thermocouple according to its location in the mollification furnace).

The quality of the multiple regression model is estimated by the determination coefficient, equal to $R^2 = 59.4\%$. The average absolute error with which the model describes the sag data is 0.22 mm, which meets the requirements.

The mollification process is monitored by recording the tensile stresses at 12 points along the perimeter of the glass. Investigations showed that it is sufficient to monitor stress at four points: CP1, CP5, CP8, and CP10 along the perimeter of the glass [7].

The average absolute error of the description by regression models of the tensile stresses ranges from 0.42 to 0.49 MPa, which is acceptable for computational determination of corrective actions.

The technological process of mollification is adjusted to a quite high degree of accuracy on the basis of the compression stresses along the border of the glass. The average absolute error of the description by models of compression stresses ranges from 1.3 to 2.3 MPa, which is acceptable for computational determination of corrective actions.

We shall use morphological modeling, specifically, the morphological box method, to choose the corrective actions for changing the temperature regime for mollification [8].

To decrease the variations of the sag of laminated glass during the fabrication process, the parameters on which the solution of the problem depends were determined by analyzing the regression equation presented above:

temperature in the preheating chamber;
temperature in the main chamber, crown;
temperature in the main chamber, bottom;
temperature in the annealing chamber.

We construct a morphological box in which the rows represent the parameters at which the temperature sensors are arranged according to the degree of decreasing influence of the variations of their indications on the sag.

TABLE 4.

Mollification regime	Standard deviation with mollification furnace temperature, °C, according to the indications of the thermocouples			Sag, mm
	22	32	45	
Before adjustment	2.4	15.7	19.5	0.49
After adjustment	1.2	7.8	9.7	0.27

Morphological Table for Choosing Corrective Actions to Stabilize Glass Sag

Mollification furnace chamber	Thermocouple code
Pre-heating chamber	19, 22, 15
Main chamber:	
crown	26, 28, 27, 32
bottom	45
Annealing chamber	49, 48

A set of values along of each row of different parameters is a possible variant of the solution of the problem being modeled. The best variant of the solution was determined by sorting possible variants. Corrective actions to decrease temperature fluctuations in the preheating chamber (thermocouple 22), on the crown of the main chamber (thermocouple 32), and at the bottom (thermocouple 45) by a factor of two must be taken for the mollification furnace (Table 4).

We shall use the morphological box method to generate corrective actions to change the tensile and compression stresses along the border of the glass (Tables 2 and 3).

The corrective actions chosen to decrease the standard deviation of the glass sag in the mollification process (see Table 4) also affect the decrease of the standard deviation of the tensile stresses at the control points CP8 and CP10, but not enough. Consequently, it was necessary to choose an additional corrective action — decrease by a factor of two the temperature fluctuations at the location of thermocouple 49 in the annealing chamber. This corrective action was sufficient to decrease the tensile stress fluctuations at the control point CP10 by a factor of 1.3.

The change in the average temperatures in the mollification furnace chambers affects the change in the average values of the tensile and compression stresses at all monitoring points along the border of the glass. We shall use a regression equation to calculate the corrective actions. The corrective actions taken to change the mollification temperature must not be contradictory — they must decrease the tensile stresses at all monitoring points (see Table 2) and increase the compression stresses at the control points CP1 and CP7 by approximately 2.4 MPa.

A combined morphological table for making decisions to change the average value of the tensile and compression stresses at the monitoring points CP1 and CP7 is constructed taking account of the consistency of the results of the corrective actions.

TABLE 5.

Decision made to correct the temperature in the mollification furnace chambers	Decrease of tensile stresses, %, at the points				Increase of the compression stresses, %, at the points			
	CP1	CP5	CP8	CP10	CP1	CP5	CP7	CP11
Increase of the temperature in the thermocouple section:								
14 by 4.5%	21.7	–	21.1	–	7.3	17.3	–	–
43 by 5.2%	17.2	–	–	–	–	–	–	–
49 by 2.3%	–	–	–	26.7	–	–	12.8	–
Decrease of the temperature in the thermocouple section:								
22 by 0.5%	–	8.6	–	–	–	–	–	–
35 by 1.8%	–	19.1	17.8	–	8.8	–	–	–
Shift of the average stress	38.9	27.7	38.9	26.7	16.1	17.3	12.8	–
Criterional requirements	38.8	27.6	26.0	24.2	16.3	–	13.0	–

Combined Morphological Table for Making Decisions to Change the Average Tensile and Compression Stresses at the Points CP1 and CP7

Mollification furnace chamber	Thermocouple code
Preheating chamber:	
crown	14, 15, 16
bottom	22, 25
Main chamber:	
crown	31, 33, 34, 35
bottom	42, 43, 45, 46
Annealing chamber	48, 49

The best solution is found by sorting through the parameters from the rows indicated. In so doing, the limitations imposed by the following quantitative criteria must be taken into account:

displacement of the center of the tensile stress distribution (see Table 2):

$$\Delta y_1 \leq -38.8\%;$$

$$\Delta y_5 \leq -27.6\%;$$

$$\Delta y_8 \leq -26\%;$$

$$\Delta y_{10} \leq -24.2\%;$$

displacement of the center of the compression stress distribution:

$$\Delta y_1 \geq 16.3\%;$$

$$\Delta y_7 \geq 13\%;$$

displacement of the centers of the temperature distributions should not shift the temperatures to outside the domain of the models.

The best variant for correcting the mollification regime of the mollification furnace by changing the average temperatures in the chambers of the furnace was determined by sorting through the data presented above (Table 5).

The computed variant of the corrections presupposes that the average temperature in the mollification furnace chambers varies in a small range — from 0.5 to 5.2%, which can be realized under production conditions.

The method proposed above for substantiating corrective actions, which was constructed on the basis of an analysis of a histogram of the distribution of the controllable parameters and using the morphological box method, can be used in glass quality control systems in glass works.

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